Paper:

Estimation of Seismic Shutoff of Intelligent Gas Meters in the Tokyo Metropolitan Area

Yoshihisa Maruyama*, **Fumio Yamazaki***, **Yoshihisa Yano****, **and Naoyuki Hosokawa****

*Department of Urban Environment Systems, Chiba University
1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
E-mail: ymaruyam@tu.chiba-u.ac.jp
**Tokyo Gas Co., Ltd.
1-5-20 Kaigan, Minato-ku, Tokyo 105-8527, Japan
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We conducted shaking-table tests to clarify the seismic shutoff features of intelligent gas meters stopping the supply of gas during earthquakes where Tokyo Gas Co., Ltd., provides service, and studied the relationship between earthquake movement and gas meter shutoff based on 200,000 monitored archive data points showing shutoff situations during actual seismic movement.

Keywords: intelligent gas meter, seismic shutoff characteristics, shaking table test, actual shutoff data

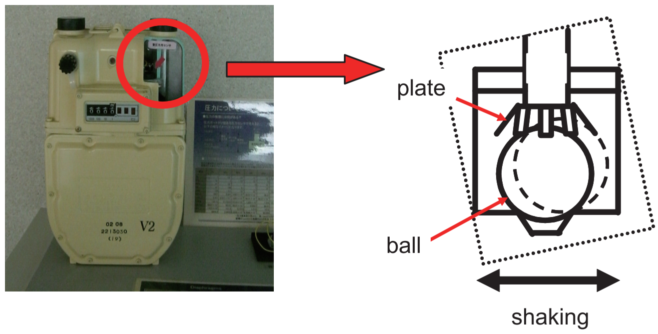


Fig. 1. Intelligent gas meter.

1. Introduction

The 1995 Kobe earthquake seriously damaged infrastructures such as the gas supply in densely populated central western Japan [1], resulting in higher postquake priority being given to antiquake measures. Tokyo Gas Co., Ltd., for one example, introduced earthquake monitoring and Seismic Information Gathering and Network Alert (SIGNAL) rapid damage assessment using 331 spectrum intensity (SI) sensors in 1994 [2]. Expanding SIGNAL to 3,800 SI sensors, the firm implemented Super-Dense Real-Time Monitoring of Earthquakes (SUPREME) in 2001 [3] whose data is to be used to assess early damage to the gas network. Results are expected to provide important information on gas supply suspension decision making.

Almost all Tokyo Gas customers are served by intelligent gas meters [4] whose use is observed and automatically stopped in gas leakage. Meters also interrupt the gas supply if peak earthquake acceleration exceeds 150-250 cm/s^2.

Meter manufacturers have been conducting product tests applying harmonic waves, but only 6 actual seismic movement records were applied to meters and only while meter prototypes were being developed, leaving uncertainty about actual seismic meter shutoff due to test limitations. In the 2005 northwest Chiba earthquake [5], many intelligent gas meters shut off gas because of shaking. The accuracy of the SUPREME subsystem used to estimate the number of meters shut off due to an earthquake is low, however, due to the uncertainty of seismic shutoff features, and an initial rapid response to an earthquake is in doubt due to potentially incorrect estimation.

To determine meter shutoff, we conducted a series of shaking-table tests applying sinusoidal waves and actual seismic movement records to meters in shaking-table tests. We also collected 200,000 shutoff archive data points after the Chiba earthquake to evaluate the relationship between recorded seismic movement and seismic meter shutoff.

2. Shaking-Table Tests

2.1. Product Tests by Manufacturers

A steel ball hitting surrounding plates in an intelligent gas meter (**Fig. 1**) [6] generates an electrical current that the meter distinguishes from other impact based on the electrical current duration. An electrical current lasting more than 40 ms three times or more in 3 s is recognized as an earthquake (**Fig. 2**).

Intelligent gas meters shut off gas if maximum input acceleration is 150-250 cm/s^2. Meter manufacturers conduct product tests in which meters undergo sinusoidal waves with periods of 0.3 s and 0.7 s (**Fig. 3**). Shutoff acceleration does not depend on the type of meter. Shutoff acceleration under a sinusoidal wave with a period of 0.3 s is essentially the same as that undergoing a sinusoidal wave with a period of 0.7 s, but product tests use only two periods for applied sinusoidal waves, making it necessary to further study seismic meter shutoff features and to consider meter shutoff acceleration under sinusoidal waves with different periods.

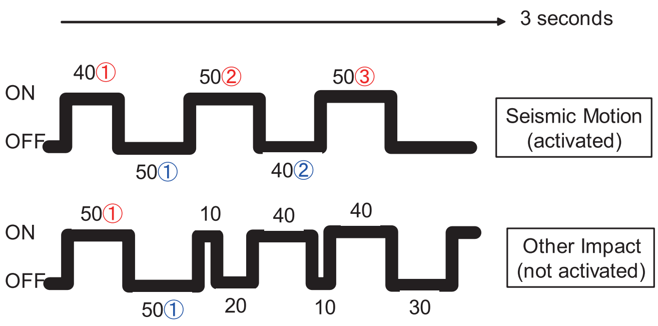
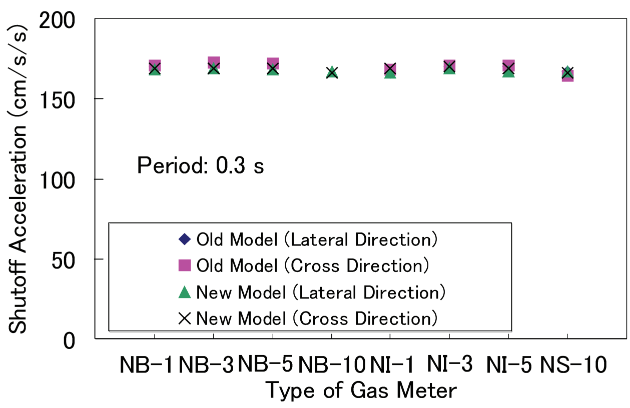
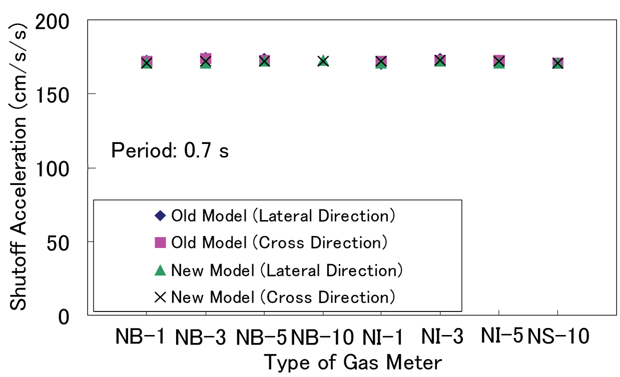


Fig. 2. Example of seismic movement recognized by intelligent gas meter.



(a)



(b)

Fig. 3. Average shutoff accelerations obtained in product tests under sinusoidal waves with periods of (a) 0.3 s and (b) 0.7 s.

2.2. Shaking-Table Tests Under Sinusoidal Waves

In a series of intelligent gas meter tests (Pipeline Technology Center, Tokyo Gas Co., Ltd.), we applied sinusoidal waves with periods of 0.1-1.8 s to meters fixed to walls (**Fig. 4**). Sinusoidal wave amplitude was increased at 5 cm/s^2 intervals. When meters shut off the gas supply, voltage was generated for 60 ms to detect the change in voltage associated with shutoff, precisely identifying when meters shut off gas. Two types of gas meters, 3 NB-3s and NB-4s each, were used in experiments.

In the relationship between the period of applied sinusoidal waves and shutoff acceleration of intelligent gas meters (**Fig. 5**), sinusoidal waves were applied in the X direction (**Fig. 4**) during shaking-table tests and the shutoff acceleration of accelerometers on gas meters obtained (**Fig. 5**, means for three gas meters). Note that one NB3-2 meter interrupted the gas supply under sinusoidal waves with a period of 0.1 s at a shutoff acceleration of 171 cm/s^2. Shutoff acceleration is almost constant when sinusoidal waves range from 0.2 to 1.8 s. These results and those of two-directional shaking tests also conducted suggest that differences in shutoff acceleration for sinusoidal wave periods are small if the period ranges from 0.2 to 1.8 s.

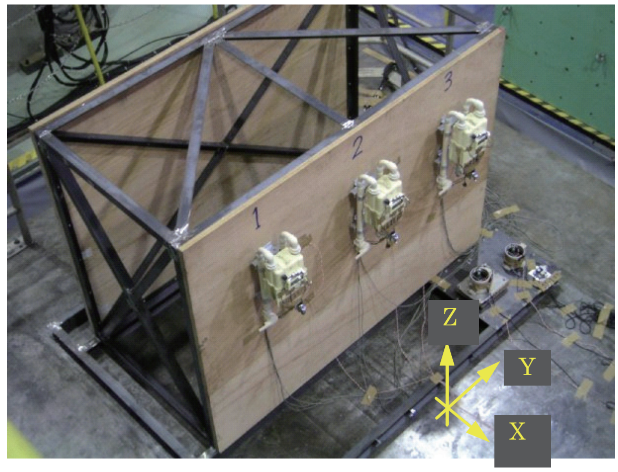


Fig. 4. Intelligent gas meters and shaking-table tests.

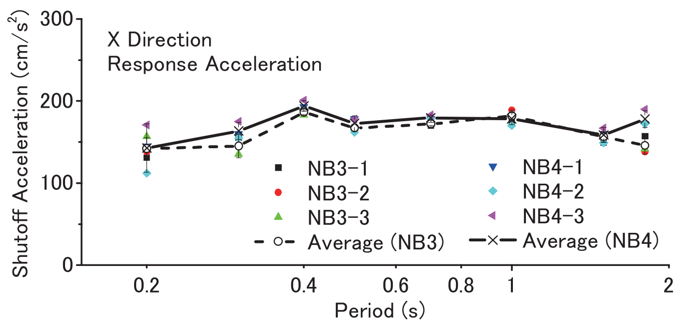


Fig. 5. Shutoff accelerations for sinusoidal waves applied in the X direction.

2.3. Shaking-Table Tests Under Actual Seismic Movement

We used three sets of seismic records as input for shaking-table tests (**Fig. 6**, acceleration response spectra (h = 0.05)) from ground movement from (1) the Kobe Marine Observatory record of the Japan Meteorological Agency (JMA) in the 1995 Kobe earthquake; (2) K-NET Yokaichiba records in the northeast Chiba earthquake on April 11, 2005; and (3) Miyako-cho Tokyo Gas seismic observation station records during the northwest Chiba Prefecture earthquake on July 23, 2005. Resultant horizontal peak ground acceleration (PGA) was scaled to 250 cm/s^2.

Table 1. Number of meters shut off in shaking-table tests according to actual seismic movement records.

	Input PGA [cm/s^2]	Observed PGA [cm/s^2]	Observed PGV [cm/s]	No. of shutoff meters	
				NB3	NB4
JMA Kobe	130	170	16.7	0	0
	150	190	19.2	3	0
	170	215	21.3	3	0
	190	242	23.6	-	3
Miyako-cho, Tokyo Gas	170	165	27.1	0	0
	190	194	30.0	3	2
	210	211	36.1	-	3
K-NET Yokaichiba	170	178	16.7	0	0
	190	202	19.3	1	0
	210	220	21.4	3	1
	230	242	22.9	-	1
	250	262	25.2	-	3

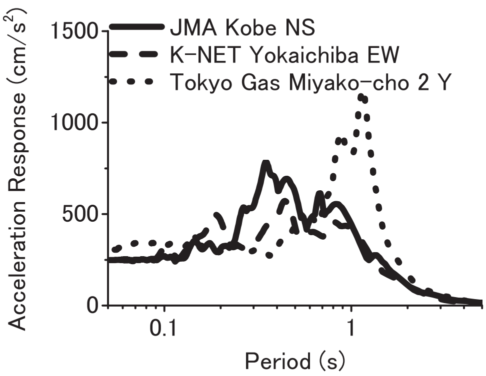


Fig. 6. Acceleration response spectra with a 5% damping ratio of ground movement records whose horizontal peak accelerations were scaled to 250 cm/s^2.

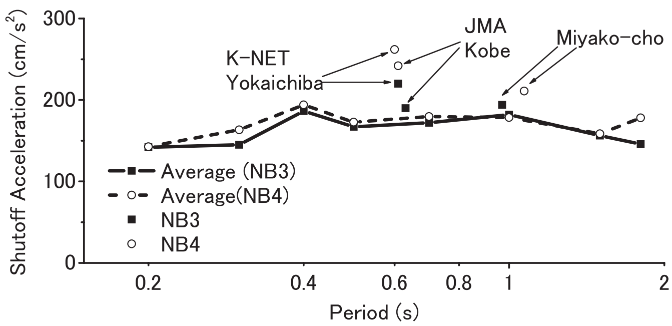


Fig. 7. Shaking-table tests under sinusoidal waves versus actual seismic records.

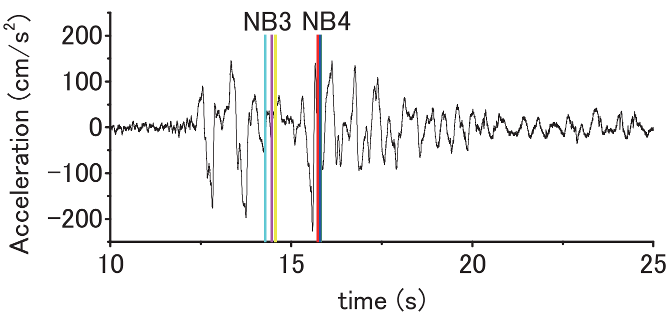


Fig. 8. Gas supply interruption by intelligent meters in JMA Kobe records.

In results of shaking-table tests (**Table 1**), differences between input and observed PGA were generated in shaking-table tests, especially for JMA Kobe records. Peak ground velocity (PGV) was calculated by integrating acceleration time histories during shaking-table tests. The period of seismic movement, T, is estimated using Eq. (1) and the relationship between shutoff acceleration and periods of ground movement determined (**Fig. 7**).

$$T = 2\pi \frac{PGV}{PGA} \quad \text{. . . . . (1)}$$

Comparing results for shaking-table tests under sinusoidal waves and seismic movement records (**Fig. 7**), we found that shutoff acceleration of NB-4 meters in JMA Kobe and K-NET Yokaichiba records was larger than under sinusoidal waves. NB-3 and NB-4 meters shut off gas at slightly different times (**Fig. 8**). NB-3 meters interrupted gas before the maximum amplitude arrived because ways of recognizing seismic movement differed for the two meters. As stated (**Fig. 2**), intelligent meters distinguish between seismic movement and other impact based on electrical current. Under another rule for recognizing seismic movement, the difference in earthquake recognition results in differences in times when meters shut off gas (**Fig. 8**).

3. Seismic Meter Shutoff Archives During the 2005 Northwest Chiba Earthquake

3.1. Dataset Collected by ST24

Tokyo Gas has introduced different antiquake systems such as STATION 24 (ST24), which observes intelligent meters detect gas leakage and suspension though telecommunications. ST24 collects meter shutoff archives.

We collected 200,000 shutoff archives after the 2005 northwest Chiba earthquake. Meters interrupting gas supply numbered 10,175. The dataset included addresses and structural types – 1- or 2-story houses, mostly wooden,

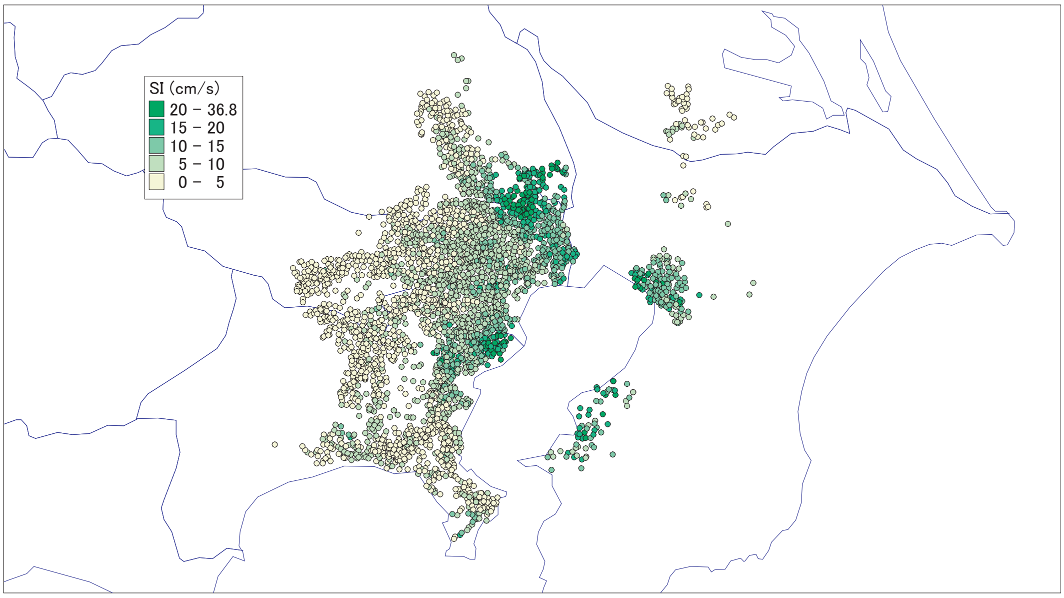


Fig. 9. JMA seismic intensity distribution in the 2005 Northwest Chiba earthquake recorded by SUPREME, Tokyo Gas Co., Ltd.

and multistory buildings. Customers applying for ST24 service were mainly owners of detached dwellings. Shutoff archives for wooden houses occupy over 75% of collected archives.

3.2. Peak Ground Acceleration Versus Meter Shutoff

SUPREME has been monitoring earthquakes and rapid damage assessment system since 2001. Ground movement records obtained by SUPREME were from 2,699 district regulators in the 2005 Chiba quake (**Fig. 9**). Ground movement amplitude depends on soil conditions, so we used meters within 500 meters of seismic observation stations to determine the relationship between meter shutoff and PGA.

Multistory building response results in differences in seismic meter shutoff related to the floor monitored (**Fig. 10**, 12-story condominium), with shutoff on higher floors greater than on lower floors because building response amplified seismic movement. According to the dataset collected, none of the 11 meters in wooden houses near this condominium cut off gas during the earthquake, indicating the need to appropriately evaluate the effects of structural response. Since most shutoff archives we collected involved wooden houses, our results held for seismic shutoff features of meters in wooden houses 1 or 2 stories high for which the effect of structural response is essentially negligible at meter locations.

In the relationship between PGA observed by SUPREME and meter shutoff in the Chiba quake (**Fig. 11**), shutoff archives for wooden houses 500 m or closer to the nearest Seismic station were used to obtain shutoff. As PGA increased, shutoff increased, but at a broad range for PGA, indicating that seismic movement might affect meter shutoff (**Fig. 12**, response spectra with

Floor	Shutoff	Non-Shutoff
12F	1	0
11F	0	0
10F	3	0
9F	1	3
8F	1	6
7F	0	4
6F	1	2
5F	1	4
4F	0	4
3F	0	3
2F	0	3
1F	0	3

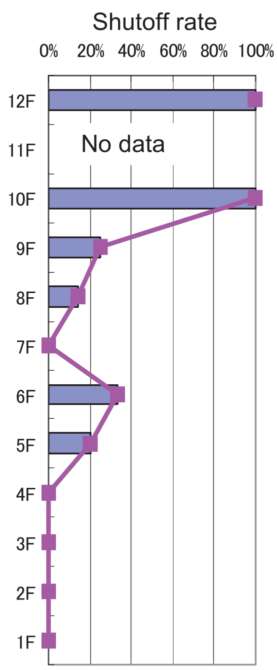


Fig. 10. Seismic meter shutoff in a 12-story building after the 2005 northwest Chiba earthquake (Chuo Ward, Chiba).

5% damping ratio at two seismic observation stations). PGA at station A was 246.0 cm/s^2 and none of the 8 meters shut off gas. PGA at station B was 217.0 cm/s^2, with all 3 meters shutting off gas. The peak response spectrum at Station A was 0.1 s. As stated, only one meter of 6 shut off gas under sinusoidal waves with a period of 0.1 s, indicating that meters are insensitive to very short-period movement, which is why none shut off gas at Station A.

In meter shutoff acceleration during the 2005 Chiba quake versus shaking-table test results during sinusoidal

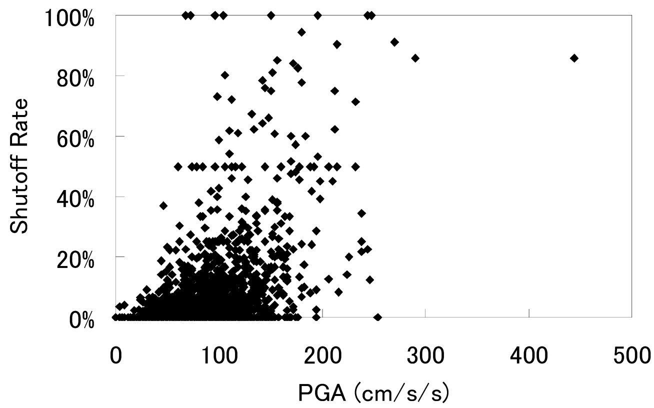


Fig. 11. PGA versus intelligent meter shutoff in wooden houses during the 2005 Northwest Chiba earthquake.

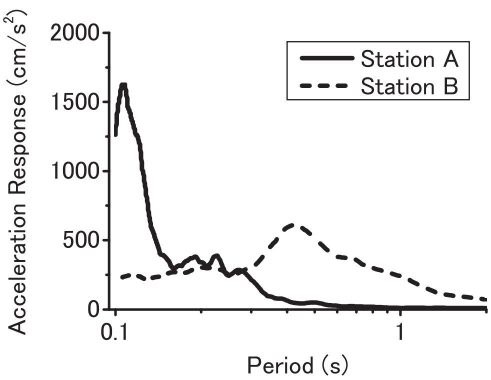


Fig. 12. Response spectra with 5% damping ratio at two seismic observation stations.

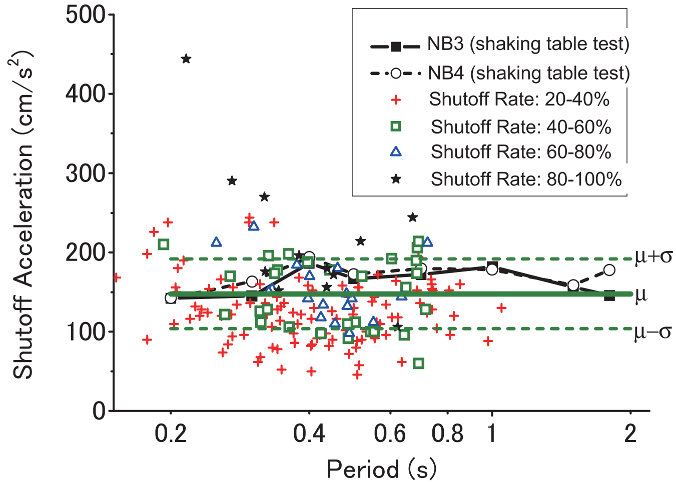


Fig. 13. Shutoff acceleration in the 2005 Chiba Northwest earthquake and in shaking-table tests with sinusoidal waves.

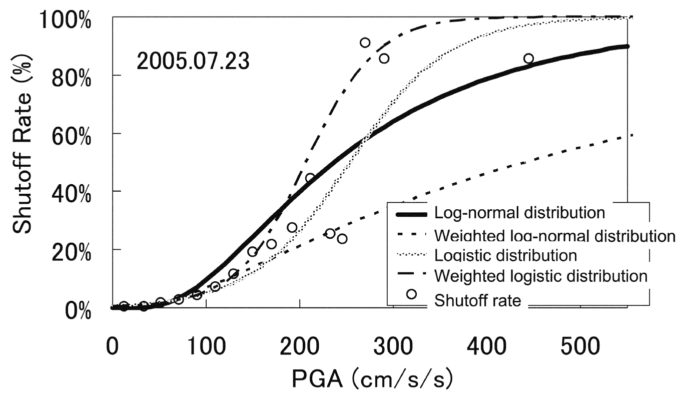


Fig. 14. Regression curves for meter shutoff in the 2005 Northwest Chiba earthquake.

waves (**Fig. 13**), meter shutoff acceleration in considering shutoffs and meter shutoff acceleration in actual cases, the spatial distribution of peak ground acceleration should be taken into account. Assuming that ground acceleration spreads with median PGA recorded at a seismic observation station, shutoff acceleration in shaking-table tests correspond to PGA associated with 50% seismic shutoff in actual cases. The average PGA associated with 40-60% seismic shutoff averaged 150 cm/s^2 – equivalent to experimentally obtained shutoff acceleration.

Thus, although meter shutoff varied widely in PGA, this can be explained based on the spatial PGA distribution in the actual environment, indicating that meter shutoff can be estimated from PGA recorded by SUPREME.

4. Estimated Meter Shutoff Curve

Tokyo Gas estimates the number of meter shutoffs after an earthquake, but the system sometimes overestimates or underestimates it, so we estimated meter shutoff using PGA observed by SUPREME. Multiplying the number of customers in a district by estimated shutoff, the number of meters shut off is predicted just after an earthquake.

We used meter shutoff archives after the 2005 Chiba quake, that after the Feb. 16, 2005, earthquake (1,596.), and after the Oct. 16, 2005, quake (1,651 shutoffs). We considered two functions in determining the estimation curve. Meter shutoff P is assumed to follow the log-normal distribution (Eq. (2)),

$$P = \Phi((\ln PGA - \lambda)/\zeta) \quad \ldots\ldots\ldots\ldots \quad (2)$$

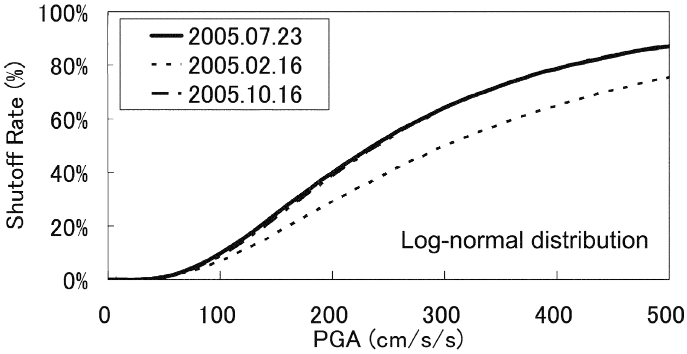
where $\Phi(x)$ is the standard normal distribution. λ is the logarithmic mean and ζ standard deviation.

Seismic shutoff is also assumed to follow the logistic distribution in Eq. (3),

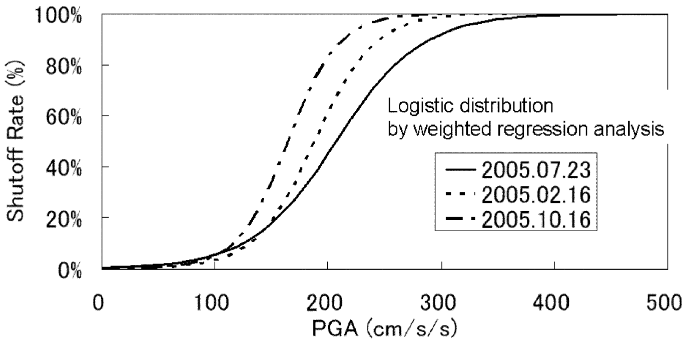
$$P = \frac{1}{1+\exp[-(\beta_0+\beta_1 PGA)]} \quad \ldots\ldots\ldots \quad (3)$$

where β_0 and β_1 are parameters in logistic distribution.

We conducted two types of regression analysis to determine parameters in Eqs. (2) and (3) using the least squares method and the weighted least squares method. The number of meters is used as a weight in weighted regression analysis (**Fig. 14**) for shutoffs in the 2005 Chiba quake. Regression curves assuming log-normal distribu-



(a)



(b)

Fig. 15. Regression curves among three earthquake events for (a) log-normal distribution and (b) logistic distribution whose parameters were determined by the weighted least squares method.

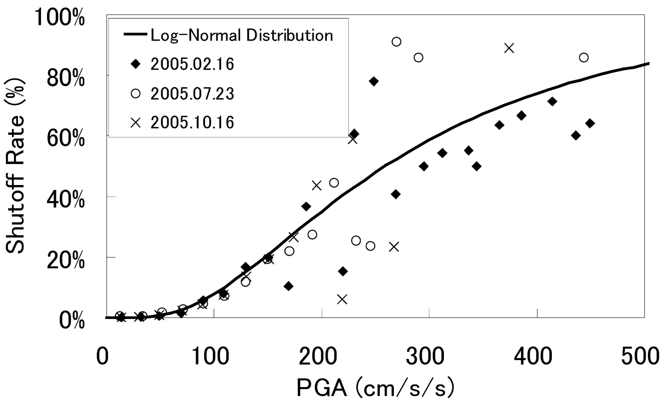


Fig. 16. Estimation curve for meter shutoff we proposed.

tion without weight and logistic distribution determined by the weighted least squares method show good estimations. Differences among earthquake events were seen for logistic distribution considering the weight for determining parameters (**Fig. 15**).

We used log-normal distribution without considering the weight to represent the relationship between PGA and meter shutoff (**Fig. 16**).

5. Conclusions

Based on shaking-table tests and statistical analysis using shutoff archives to clarify seismic shutoff features of intelligent gas meters, we found that shutoff acceleration under sinusoidal waves was essentially constant for the period of sinusoidal waves. The fact that meters did not interrupt gas supply at an applied movement of 0.1 s indicates that meters are not sensitive to very short-period ground excitation.

From estimation curves for meter shutoff constructed based on PGA values observed by SUPREME and shutoff archives collected by ST24, we found that only shutoff datasets of meters in detached, mostly wooden dwellings did not include the effects of structural response to ground movement. Further research is thus needed to clarify effects of structural response to seismic meter shutoff.

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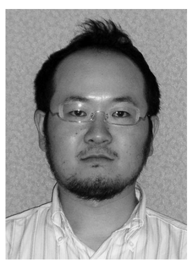

Name:
Yoshihisa Maruyama

Affiliation:
Assistant Professor, Department of Urban Environment Systems, Chiba University

Address:
1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

Brief Career:
2004 Completed Doctor course of Graduate School, Dept. of Civil Engineering, The University of Tokyo
2004- Postdoctoral Research Fellow, Center for Urban Earthquake Engineering, Tokyo Institute of Technology
2005- Research Associate, Department of Urban Environment Systems, Chiba University

Name:
Fumio Yamazaki

Affiliation:
Professor, Department of Urban Environment Systems, Chiba University

Address:
1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

Brief Career:
1978 Completed Master course of Graduate School, Dept. of Civil Engineering, The University of Tokyo
1978- Shimizu Corporation
1989- Associate Professor, Institute of Industrial Science, The University of Tokyo
2001- Professor, Asian Institute of Technology (AIT), Bangkok, Thailand
2003- Professor, Department of Urban Environment Systems, Chiba University

Name:
Yoshihisa Yano

Affiliation:
Tokyo Gas Co., Ltd.

Address:
2-5-19 Minami-Azabu, Minato-ku, Tokyo 106-0047, Japan

Brief Career:
2005 Graduated from Department of Urban Environment Systems, Chiba University
2007 Completed Master course of Graduate School, Department of Urban Environment Systems, Chiba University
2007 Tokyo Gas Co., Ltd.

Name:
Naoyuki Hosokawa

Affiliation:
Supply and Disaster Management Department, Tokyo Gas Co., Ltd.

Address:
1-5-20 Kaigan, Minato-ku, Tokyo 105-8527, Japan

Brief Career:
1994 Graduated from Department of Civil Engineering, The University of Tokyo
1996 Completed Master course of Graduate School, Dept. of Civil Engineering, The University of Tokyo
1996 Tokyo Gas Co., Ltd.